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LCA OF WASTE MANAGEMENT SYSTEMS

Life cycle assessment of composite packaging waste management—a Chinese case study on aseptic packaging

Minghui Xie · Qi Qiao · Qihong Sun · Linlin Zhang

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Abstract
Purpose Approximately 46,000 t/day of packaging waste was generated in China in 2010, of which, 2,500 t was composite packaging waste. Due to the lack of recycling technology and an imperfect recovery system, most of this waste is processed in sanitary landfills. An effective packaging waste management system is needed since this waste not only uses up valuable resources, but also increases environmental pollution. The purpose of this study is to estimate the environmental impact of the treatment scenarios in composite packaging waste which are commonly used in China, to determine the optimum composite packaging waste management strategy, and to design new separating and recycling technology for composite packaging, based on the life cycle assessment (LCA) results.
Methods To identify the best treatment for composite packaging waste, the LCA software SimaPro 7.1.6 was used to assist in the analysis of the environmental impacts, coupled with the impact assessment method Eco-Indicator 99. LCA for composite packaging waste management was carried out by estimating the environmental impacts of the four scenarios most often used in China: landfill, incineration, paper recycling, and separation of polyethylene and aluminum. One ton of post-consumption Tetra Pak waste was selected as the functional unit. The data on the mass, energy fluxes, and environmental emissions were obtained from literature and site investigations.
Results and discussion Landfill—scenario 1—was the worst waste management option. Paper recycling—scenario 3—was more environmentally friendly than incineration, scenario 2. Scenario 4, separating out polyethylene and aluminum, was established based on the LCA result, and inventory data were obtained from the demonstration project built by this research. In scenario 4, the demonstration project for the separation of polyethylene and aluminum was built based on the optimum conditions from single-factor and orthogonal experiments. Adding this flow process into the life cycle of composite packaging waste treatment decreased the environmental impacts significantly.
Conclusions The research results can provide useful scientific information for policymakers in China to make decisions regarding composite packaging waste. Incineration could reduce more environmental impacts in the respiratory inorganics category, and separation of polyethylene and aluminum, in the fossil fuel category. If energy saving is the primary governmental goal, the separation of polyethylene and aluminum would be the better choice, while incineration would be the better choice for emission reduction.

Keywords Aseptic package · Composite packaging waste · Separation of polyethylene and aluminum · Waste management

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M. Xie (✉)
State Key Laboratory of Environmental Criteria and Risk Assessment, Key Laboratory of Eco-Industry of the Ministry of Environmental Protection,
Chinese Research Academy of Environmental Sciences,
Beijing 100012, People's Republic of China
e-mail: huibird82@163.com

Q. Qiao (✉) · Q. Sun
Key Laboratory of Eco-Industry of the Ministry of Environmental Protection,
Chinese Research Academy of Environmental Sciences,
Beijing 100012, People's Republic of China
e-mail: qiaoqi@craes.org.cn

L. Zhang
China National Environmental Monitoring Centre,
Beijing 100012, People's Republic of China

1 Introduction

Packaging is a fundamental element of almost every manufactured product. Because of the relatively short life cycle of many consumer products, the volume of packaging on the market is almost exactly equal to the volume of packaging waste. In China, the volume of packaging materials is increasing each year, as is the number of manufacturers producing these materials, to the point where packaging waste now represents approximately 15 % of municipal solid waste by weight (Jin et al. 2008; Zhou et al. 2010). Most of the packaging waste is composite packaging (primarily PA-PE-Al laminate, a laminated foil made from paper, polyethylene, and aluminum foil)—material that is difficult to recycle because of relatively high cost and low resale value. Composite packaging, in particular, is unattractive to recycling processors because both the packaging waste recycling system and the composite packaging reuse technologies are relatively undeveloped in China. And although the Chinese government, in an attempt to reduce the increasing amount of packaging waste, announced GB 23350-2009 Requirements of restricting excessive package—foods and cosmetics (AQSIQ and SAC 2009) in March, 2009, the practical effect of this regulation has so far been insignificant.

To alleviate public concerns over the increasing rate of resource consumption and waste production, policy makers have encouraged recycling and reuse strategies, to reduce the demand for raw materials and decrease the quantity of waste going into landfills. However, these strategies have also been criticized because of their possible contributions to other types of resource and environmental impacts, which, while less obvious, are no less important. For example, the environmental benefits of recycling paper have been questioned in light of studies that have shown that they increase fossil fuel consumption and emissions of greenhouse and acidifying gases (Wang and Hua 2006). No matter how waste packaging materials are treated, increasing the consumption of materials increases the environmental burden. It is therefore necessary to perform a comprehensive environmental impact assessment of the treatment of packaging waste.

Life cycle assessment (LCA), an environmental management tool that can solve the above-mentioned problems, has been developing rapidly over the past several years. There have been extensive LCA case studies on the environmental performance of a number of different packaging systems, including the environmental impacts of PLA, PET, and PS clamshell containers (Madival et al. 2009), the selection of materials for beverage packaging in Brazil (Almeida et al. 2010), the reuse and recycling of a plastic-based packaging system (Ross and Evans 2003), the production of egg containers from polystyrene and recycled paper (Zabaniotou and Kassidi 2003), and so forth. And a wide range of LCA studies of waste management has been conducted, such as life cycle assessments of solid waste management options (Banar et al. 2009; Mendes et al. 2004; Boer et al. 2007; Hong et al. 2010), EASEWASTE and WASTED models for life cycle assessment of municipal solid wastes (Kirkeby et al. 2007; Diaz and Warith 2006), environmental comparison of biosolids management systems (Peters and Rowley 2009), and a life cycle impact assessment of various waste conversion technologies (Khoo 2009). Although there have been extensive LCA case studies on packaging or municipal solid waste (MSW), and some LCA reports of composite packaging such as Tetra Pak production, life cycle assessment of packaging waste management studies has been very limited (Villanueva and Wenzel 2007; Schmidt et al. 2007; Merrild et al. 2008). Moreover, those reports focused on packaging production and were retained within the producing company as commercial confidential information. It has been difficult, therefore, to obtain any LCA studies on packaging, in the published literature. There is only one study, from the ScienceDirect database, assessing the environmental effects of an increase in the recycling rate of composite packaging waste in Brazil (Mourad et al. 2008). Moreover, no composite packaging waste management has been studied. In addition, although interest in LCA as a method of research has been growing globally, it has attracted less attention in China, both quantitatively and qualitatively. To address this inadequacy, composite packaging waste was chosen as an LCA research project based as much as possible on local Chinese data.

Thus, in this paper, LCA was conducted: (1) to estimate the environmental impacts of the treatment scenarios in composite packaging waste which are commonly used in China, (2) to identify the best treatment for composite packaging waste, and (3) to design new separation and recycling technology of composite packaging based on the LCA results. The expectation was to provide useful scientific information for policymakers in China, so that they could make decisions regarding composite packaging waste management, and to help increase the life cycle inventory database of China.

2 Methodology

The broad perspective of LCA makes it possible to take into account the significant environmental benefits that can be obtained through different waste management processes. For instance, incineration with energy recovery reduces the need for other energy sources, and material from recycling processes can replace virgin material (Ekvall et al. 2007). Some models have also been developed, that can perform LCA simulations of waste management systems, thereby allowing the analysts, through scenario analysis, to determine how proposed changes in the system would affect the

environmental impacts (Winkler and Bilitewski 2007). This study was conducted according to the recommendations of the International Standards Organization (ISO) 14044-2006 Environmental management—Life cycle assessment—Requirements and guidelines (ISO 2006).

2.1 Functional unit and boundaries of the system

The definition of a functional unit in waste management LCA is different from that in product LCA. In a product LCA, the functional unit is usually defined in terms of the system's output, i.e., the product (for example, per liter of packaging container or per number of coffee pots produced). In the case of waste management, though, since the function of the system is to make waste disappear, the waste of one household, or the total waste of a defined geographical region in a given time (e.g., 1 year) can be chosen as the functional unit.

The most typical composite package in China is an aseptic package used for long-life protection of perishable products such as milk and juice. Some representative aseptic packages are: Tetra Pak, produced by Tetra Pak Co. Ltd.; SIG Combibloc by SIG Combibloc Co. Ltd.; and Gable-top Box by Shanghai International Paper CNPC Ltd. All of these packages have similar structures and are laminated single- or multi-layered paper, polyethylene, and aluminum in an opaque, antioxidant and damp-proof aseptic environment. Since this type of packaging constitutes the majority of packaging in China, 1 t of post-consumption Tetra Pak waste was defined as the aseptic packaging waste functional unit for this study. This waste is composed of a carton, polyethylene, and aluminum foil composite material, respectively, accounting for 75, 20, and 5 % by weight.

Four different waste treatments were investigated in this assessment (the collection and per-sort were not investigated because those were assumed to be the same for all scenarios). The system boundaries for each scenario are shown in Fig. 1. All of these scenarios considered only the environmental impact of their operation and did not quantitatively present the environmental impacts of buildings or equipment. (Scenario 4 is discussed later in this study.)

Scenario 1 (landfill) Aseptic packaging waste is delivered to the landfill with no further treatment. The system boundary of scenario 1 is shown in Fig. 1.

Scenario 2 (incineration) Aseptic packaging waste is directly transported to the incineration plant in order to produce electricity through combustion. It has a lower heating value of 46.88 MJ/kg, which was measured by thermogravimetric analysis–differential thermal analysis–Fourier transform infrared spectroscopy. This energy is then converted to 3,872 kWh of electricity, calculated by analogy with the heat value of municipal solid waste from the Incineration G plant in Beijing, whose heat recovery system is not optimal. The system boundary of scenario 2 is shown in Fig. 1.

Scenario 3 (paper recycling) As paper represents 75 % of the total aseptic package mass, the recycled aseptic package is an excellent source of raw material for producing recycled paper. The cellulose material from the post-consumption aseptic packaging gives high quality fibers (around 90 % of the total fiber content), most of which are recovered by a paperboard company and reused in the production of kraft paper. The polyethylene and aluminum residues are generated by the recovery of cellulose from the post-consumption aseptic packages; these are processed in sanitary landfills. The system boundary of this scenario is shown in Fig. 1.

2.2 Data collection

2.2.1 Municipal waste disposal

Although there have been extensive LCA case studies on MSW, they are not consistently similar to the conditions in China, where more than 50 wt% of municipal solid waste is food residue, which is more perishable and has a high water content. This situation differs from other countries such as Japan and Brazil and European countries. The treatment processes and inventories also differ. Therefore, it is difficult to apply information obtained from foreign LCA studies on MSW, to China. So far, there have been only four LCA case studies published in English language peer-reviewed journals about LCA applied to MSW in China (Hong et al. 2010; Hong et al. 2006; Zhao et al. 2009a, b), and only one case study has been published about LCA applied to PA-PE-Al laminate packaging in China (Xie et al. 2011). Hong et al. (2006) did not conduct environmental analyses of electricity recovery from methane gas from landfills. Zhao et al. (2009a) discussed only the environmental potential impact on global warming. Hong et al. (2010) and Zhao et al. (2009b) assessed only the environmental impacts of the current municipal solid waste management system, and Xie et al. (2011) compared only the environmental impacts of recycling the paper from milk packaging systems, after extracting the PA-PE-Al laminate and polyethylene, and did not discuss the environmental impacts of other treatment methodologies. Overall, there has been a noticeable lack of significant information on packaging waste management, whether in English or in Chinese. Accordingly, additional research is needed to address issues omitted from other studies, to provide a more reliable and thorough assessment of packaging waste management in China.

The data for life cycle inventory of landfill or incineration in this study were gathered from the Ecoinvent database. The data quality indicators option of the software was used

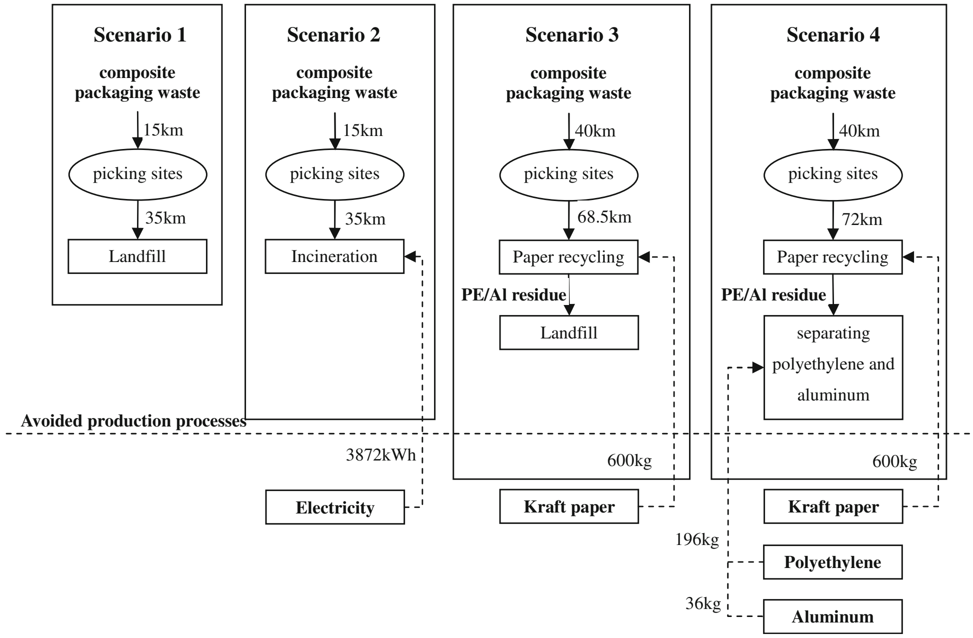

Fig. 1 Scenario system boundaries

to select the most suitable system for data quality indicators such as time, geography, technology, and representativeness.

2.2.2 Paper recycling

As composite packaging waste can provide an excellent raw material for kraft paper, data relating to the consumption and emissions from the recovery of cellulose obtained from composite packaging waste come from site investigations of two composite package recovery factories in China. The polyethylene and aluminum residues generated by the recovery of cellulose from the composite package are difficult to separate and reuse completely. Thus, this residue is processed in sanitary landfills due to lack of separation technology. The life cycle inventory data of kraft paper production and landfill residue were all obtained from the Ecoinvent database.

2.2.3 Life cycle inventory for energy

In China, electricity from public utility services is produced by and distributed via an interconnected system of electricity plants fueled by nonrenewable sources. The main aspects (consumption and emission) related to the extraction and production of fossil fuels (precombustion), such as fuel oil, coal, and natural gas, have been included within the boundaries of this study. The data concerning the generation and distribution of electricity in China are based on the study carried out by Chinese researchers Di et al. (2005) and Liu et al. (2010). The inventory data from Liu et al. (2010) were also referred by the Chinese Life Cycle Database (Liu et al. 2010). The life cycle inventories for the production of coal used for paper recycling in China were calculated by Yuan et al. (2006) and involve the consumption of raw coal and the emissions produced during its life cycle.

2.2.4 Transportation

The transport distances were calculated based on the average distances between each plant by site investigation. The most significant transport distances are: 15 km for the transportation of post-consumption packages to the waste pick-up sites (for transitory storage only) by van (2 mt); 35 km for the transportation from the waste pick-up sites to the landfill or incineration by diesel truck (10 mt); 40 km for the transportation of post-consumption packages to the recycling pick-up sites (for transitory storage only) by van (2 mt); and 68.5 km for the transportation from the recycling pick-up sites to the paper recycling plant by diesel truck (10 mt). The life cycle inventory data concerning the extraction and production of diesel oil and fuel oil and the environmental emissions from the operation of road transportation in China are based on the study carried out by Chinese researchers Ma et al. (2006) and Liu et al. (2008).

2.2.5 Allocation procedures

All impacts from the subsequent landfill, incineration, and recycling processes are assigned to the input material. However, there is a need for allocation to account for the benefits of recycling and energy recovery processes modeled in this study. Waste management technologies produce different types and quantities of recycled/reprocessed products—energy, fuel, secondary raw materials, etc. Therefore, a fair comparison of these technologies must account for both the impacts of the process and the benefits of the products. This LCA study uses a system

Table 1 Life cycle inventories for each scenario per functional unit

Scenario 1	Scenario 2	Scenario 3	Scenario 4
Input			
Transportation via van (2 mt), 15 tkm	Transportation via van (2 mt), 15 tkm	Transportation via van (2 mt), 40 tkm	Transportation via van (2 mt), 40 tkm
Transportation via truck (10 mt), 35 tkm	Transportation via truck (10 mt), 35 tkm	Transportation via truck (10 mt), 68.5 tkm	Transportation via truck (10 mt), 72 tkm
Electricity, 0.96 kWh	Natural gas, 0.06 kg	Coal, 301 kg	Coal, 301 kg
HDPE, 0.19 kg	Electricity, 66.7 kWh	Electricity, 380 kWh	Electricity, 550 kWh
Diesel, 0.62 kg			Diesel, 3.43 kg
			Formic acid, 39.3 kg
Output			
	Electricity, 3,872 kWh	Kraft paper, 600 kg	Kraft paper, 600 kg
			Polyethylene, 196 kg
			Aluminum, 36 kg

HDPE high-density polyethylene

expansion approach to calculate the overall environmental performance of each scenario as follows:

$$\begin{matrix}\text{Environmental} \\ \text{performance}\end{matrix} = \begin{matrix}\text{process} \\ \text{impacts}\end{matrix} - \begin{matrix}\text{avoided impacts of} \\ \text{primary production}\end{matrix}.$$

The life cycle inventories for these scenarios are presented in Table 1.

2.3 Impact assessment

In the present study, the Eco-Indicator 99 method was used for the impact assessment step because it is a damage-oriented and endpoint approach proceeding from the identification of areas of concern (damage categories) to the determination of what causes the damage (Pre 2007). The Eco-Indicator 99 method considers three damage categories: Human health (disability adjusted life years), ecosystem quality (potentially disappeared fraction, on a certain area during a certain time period), and depletion of resources (surplus energy for future extraction). For further interpretation, the results are integrated to one indicator using common weighting to keep the integration step transparent. The weights for human health, ecosystem quality, and resources were 40, 40, and 20 %, respectively. This weight distribution is always used in Chinese LCIA research. In this study, eight impact categories included in the EI99 method were investigated: carcinogens, respiratory inorganics, climate change, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels.

3 Results

The characterization results of each scenario are reported in Table 2. The characterization result of every category in scenario 1 is a positive value, which indicates an adverse environmental impact. Since electricity is recovered through combustion in scenario 2, environmental impacts of kraft paper production are avoided in scenario 3, and those of the production of kraft paper, polyethylene, and aluminum production are avoided in scenario 4; the characterization results

Table 2 Characterization results of each scenario

Impact categories	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Carcinogens (CA)	DALY	6.24E−4	−6.01E−5	4.65E−4	−1.85E−4
Respiratory inorganics (RI)	DALY	4.87E−5	−3.82E−3	4.14E−4	−8.7E−5
Climate change (CC)	DALY	2.44E−4	−3.86E−4	4.24E−4	1.56E−4
Ecotoxicity (ET)	PDF ($m^2 year^{-1}$)	12.2	−46.1	−11.9	−28.4
Acidification/eutrophication (AE)	PDF ($m^2 year^{-1}$)	1.40	−162	26.4	22.8
Land use (LU)	PDF ($m^2 year^{-1}$)	1.76	0.352	−692	−710
Minerals (MI)	MJ surplus	0.63	1.29	−16.9	−189
Fossil fuels (FF)	MJ surplus	57.1	−242	−558	−3,610

DALY disability adjusted life year, *PDF* potentially disappeared fraction

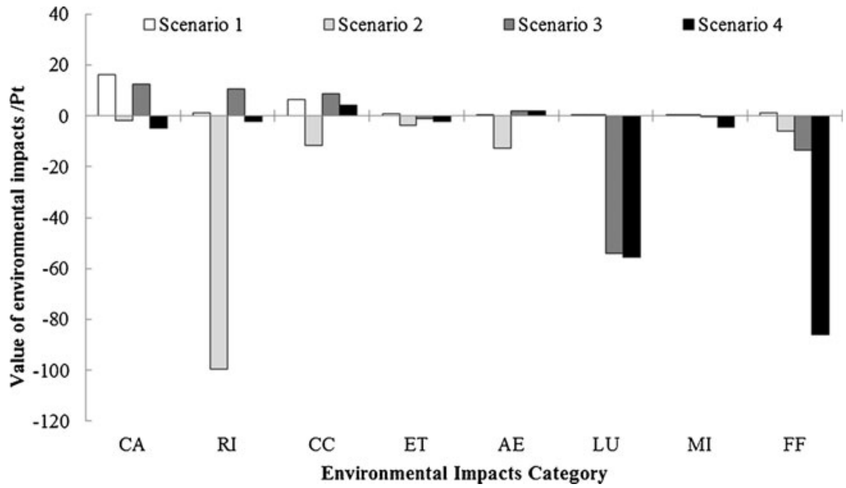

Fig. 2 Scenario assessment results and comparison per impact category

of scenarios 2, 3, and 4 are mostly negative values, meaning that they have a beneficial effect on the environment.

The results of the functional unit per impact category are reported in Fig. 2. The length of the column represents the magnitude of the impact.

Scenario 1 The potential value of the total environmental impact from the landfill of 1 t of post-consumption Tetra Pak waste is 26.5 Pt. The carcinogens (16.3 Pt) and climate change (6.4 Pt) categories exhibit a high contribution because of cadmium from waterborne emissions and greenhouse gases from cartons in landfills. Cadmium has always been used to stabilize plastic in manufacturing (Morrow 2010). The carbon dioxide and methane emissions from landfills were 297 and 40.5 kg, respectively.

Scenario 2 The potential value of the total environmental impact from incineration is −133 Pt. The respiratory inorganics (−99.4 Pt) category had the largest impact because of avoided coal burning airborne emissions in the Chinese electricity grid; these were 34.7 kg SO_2 and 22.0 kg NO_x. Other categories also contributed to avoided emissions through electricity production recovery, although at lower levels.

Scenario 3 The potential value of the total environmental impact from paper recycling is −34.9 Pt. The land use (−53.9 Pt) category has a major significance for paper recycling process in this scenario because it reduces the need for producing equivalent kraft paper from primary materials. The fossil fuels (−13.4 Pt) category has minor

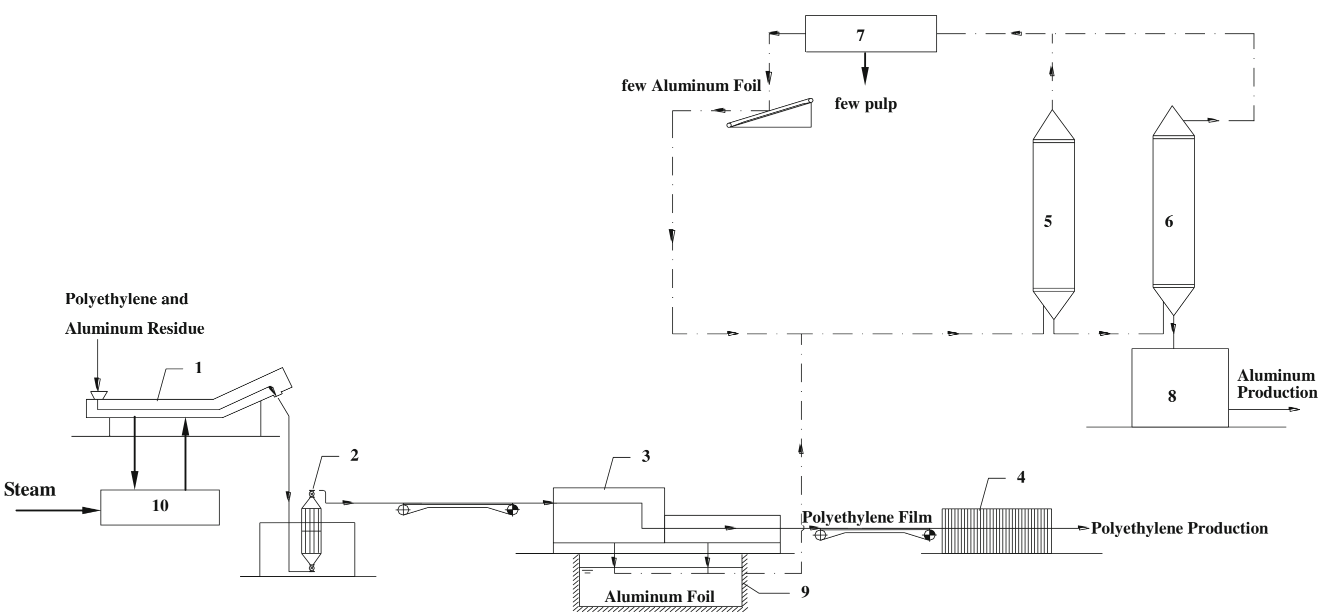

Fig. 3 Operating process flow of separation: *1* Continuous soaking reactor tank, *2* centrifugal dry machine, *3* centrifugal screen machine, *4* baling and granulator, *5* centrifugal cleaner I, *6* centrifugal cleaner II, *7* pulp screen, *8* melting furnace, *9* sedimentation tank, *10* heating transfer

significance, however, for avoiding the use of primary materials for the production of kraft paper, although this process does reduce the environmental impact in the respiratory inorganics (10.6 Pt) category. In addition, the avoided impact of kraft paper production from primary materials is smaller than the avoided impacts of NO_x and SO_2 airborne emissions from coal burning and electricity production. Consequently, the respiratory inorganics category still has negative impacts. In the carcinogens (12.5 Pt) category, cadmium in the waterborne emissions from landfills is the most significant aspect with a high value (13.2 Pt); hence, this is the major contributor to the avoided impacts of kraft paper production in this category (−1.59 Pt). The contribution of the climate change (8.81 Pt) category comes mainly from CO_2 airborne emissions from coal burning, electricity production, and the avoided impacts of kraft paper production.

Considering that the polyethylene and aluminum residues are processed in sanitary landfills, the environmental impacts from paper recycling can be decreased more significantly by separating out the polyethylene and aluminum. But the separation of polyethylene and aluminum from packaging is still in the beginning stages in China, and generally the bulk of these materials will be processed in sanitary landfills. This situation results not only in resource waste, but in secondary pollution as well. If the polyethylene and aluminum could be completely separated out into pure polyethylene and pure aluminum, not only could their reuse values be fully realized, but the raw materials consumed in their manufacture could be reduced. Therefore, the extraction of polyethylene and aluminum from composite packaging could reduce the life cycle environmental impacts of this packaging significantly.

4 Scenario 4: separating out polyethylene and aluminum

4.1 Optimum conditions and process flow

After recycling the paper, in the remaining residue, polyethylene accounts for 80 % and aluminum 20 %. The extraction of polyethylene and aluminum from packaging waste has attracted extensive attention recently. According to Zuben (2006), Tetra Pak started to recover aluminum and produce paraffin from residue using a plasma process (~15,000 °C), in 2005. However, because of the high cost and energy consumption, the plasma process is not yet available in China.

Since 2005, many plants and research institutes in China have been working together to separate polyethylene and aluminum through a wet process, but most of them focus only on the selection of the separation reagents and the design of a separating device, which is insufficient for extensive production. This study, though, was conducted by a team from the Chinese Research Academy of Environmental Sciences

Table 3 The contributions of the main process (in point)

Main process	CA	RI	CC	ET	AE	LU	MI	FF	CA	RI	CC	ET	AE	LU	MI	FF
	Scenario 1								Scenario 2							
Transportation	3.19E−3	0.623	3.69E−2	0	3.94E−2	0	0	0.399	3.19E−3	0.623	3.69E−2	0	3.94E−2	0	0	0.399
Landfill	16.3	0.169	6.31	0.951	6.13E−2	0.137	1.50E−2	0.961								
Incineration									3.07	1.52	11.5	0.567	0.251	2.74E−2	3.07E−2	0.830
Recover electricity									−4.64	−102	−21.6	−4.17	−12.9	0	0	−6.99
Main process	Scenario 3								Scenario 4							
	CA	RI	CC	ET	AE	LU	MI	FF	CA	RI	CC	ET	AE	LU	MI	FF
Transportation	6.35E−3	1.26	8.39E−2	0	0.101	0	0	0.91	6.85E−3	1.35	8.72E−2	0	0.107	0	0	0.945
Paper recycling	−0.996	8.88	8.67	−1.46	1.89	−54.1	−0.416	−14.9	−0.996	8.88	8.67	−1.46	1.89	−54.1	−0.416	−14.9
Landfill of PE/Al residue	13.5	0.113	0.115	0.444	1.26E−2	3.43E−2	2.98E−3	0.247								
Separation of PE/Al residue									−3.82	−12.4	−4.68	−0.756	−0.212	−0.312	−4.08	−72.1

CA carcinogens, *RI* respiratory inorganics, *CC* climate change, *ET* ecotoxicity, *AE* acidification/eutrophication, *LU* land use, *MI* minerals, *FF* fossil fuels

which is undertaking the key project of a scientific support program as stated in the 11th Five-Year Plan of China "Resource Utilization Technology of Packaging Waste" under the "Key Technology and Demonstration Research of Clean Production and Recycling Economy" and focuses on the separating and recycling technology of polyethylene and aluminum in aseptic packaging waste; this project has made several achievements.

By single-factor and orthogonal experiments, the optimum condition of polyethylene and aluminum complete separation using formic acid as separation reagent was obtained: 4 mol/L of formic acid concentration, 60 °C of reaction temperature, 60 L/kg of liquid-to-solid ratio, and 5×5 cm of solid size. Under these conditions, the separation rate reaches 100 %, the separating time is 25 min, and the aluminum loss rate is 4.73 %. The flow diagrams, equipment, and chemical consumption for this process are shown in Fig. 3.

The separation process is a chemical and mechanical one. Only one chemical additive, formic acid, is added into the continuous soaking reactor tank, using steam to keep the temperature at 60 °C. The reaction tank rotates, to make the chemical additive mix with the residue uniformly, and an internal guiding bar separates out polyethylene and aluminum. Screens separate polyethylene film and aluminum foil according to size differences, and centrifugal parts separate aluminum foil according to weight differences.

4.2 Data collection and impact assessment

The data on consumption and emissions related to the separation of polyethylene and aluminum derived from residue were taken from site investigation of the demonstration project for the separation of polyethylene and aluminum, in Zhejiang Province, China, operated by Hangzhou Fulun Ecology Technology Co., Ltd. This factory was designed and built using the latest available best practices for process flow and has been running well for 2 years. For the functional unit used in this study, the consumption data in this separation process were: 170 kWh of electricity, 3.43 kg of diesel, 3.47 tkm for transportation by diesel truck (10 mt), and 39.3 kg of formic acid; the production outputs were 196 kg of polyethylene and 36 kg of aluminum.

4.3 Results

The same impact assessment method was used for all scenarios; the results are shown in Fig. 2. The value of the potential environmental impact per functional unit was −150 Pt. It is noticeable that in all the impact categories, impacts are more or less avoided in total, especially in the fossil fuels (−86.0 Pt) and land use (−55.4 Pt) categories. Avoided impacts in the land use category are attributable to paper recycling, which is the same as for scenario 3. The separation and recycling of polyethylene and aluminum are the main contributors to the savings from the depletion of fossil fuels and minerals. As aluminum represents only 5 % of the total packaging waste mass, avoided impacts in the minerals category (−4.50 Pt) for aluminum recycling are less obvious. In the carcinogens (−4.81) category, because of the lack of processing in landfills, the positive environmental impacts come entirely from the avoided impacts of paper, polyethylene, and aluminum recycling processes. The environmental impacts of the other categories also decreased for the same reasons.

This study introduces four composite packaging waste treatment management scenarios in China. The results show that scenario 1 is the worst waste management option, and that scenario 2 is more environmental-friendly than scenario 3. In scenario 4, the demonstration project for the separation of polyethylene and aluminum was built based on the optimal conditions from single-factor and orthogonal experiments. By adding this flow process to the life cycle of composite packaging waste treatment, the environmental impacts were decreased 12.8 % below those of scenario 2.

5 Process contribution and sensitivity analysis

The main process contributions—transportation, landfill, incineration, electricity recovery, paper recycling, and the

Table 4 Results of the sensitivity analysis

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Transportation distance (±10 %)	±0.38 %	±0.075 %	±0.61 %	±0.17 %
Electricity production (±10 %)	–	±11.28 %	–	–
Kraft paper production (±10 %)	–	–	±26.91	±6.00 %
Polyethylene production (±10 %)	–	–	–	±5.47 %
Aluminum production (±10 %)	–	–	–	±3.03 %
Formic acid consumption (±10 %)	–	–	–	±0.90 %
Coal consumption (±10 %)	–	–	±6.12 %	–
Electricity consumption (±10 %)	–	–	±5.05 %	±1.87 %

– means no parameter in this scenario

handling of polyethylene and aluminum residue (both in the landfill and in the separation process)—were performed for each scenario. The results are shown in Table 3.

The processes of electricity recovery in scenario 2 and paper recycling in scenario 3 contribute the most to the decrease of environmental impacts, especially for the respiratory inorganics (−102 Pt) and land use (−54.1 Pt) categories. Avoided environmental impacts in the respiratory inorganics category of the first are 67.0 % of the entire avoided environmental impacts from electricity recovery, and those in the land use category of the second are 74.9 % of the entire avoided environmental impacts of kraft paper production. The process of separating out polyethylene and aluminum residue, in scenario 4, avoids the environmental impact in the fossil fuel (−72.1 Pt) and mineral (−4.08 Pt) categories, compared to scenario 3. Avoided environmental impacts in the fossil fuel category make up 73.3 % of the entire avoided environmental impacts, and this processing also avoids environmental impacts in the respiratory inorganics (−12.4 Pt, 12.6 %) category. As aluminum represents only 5 % of the total packaging waste mass, however, avoided impacts in the minerals category are not readily apparent.

Sensitivity analysis was also performed, using transportation distance, electricity production, kraft paper production, polyethylene production, aluminum production, formic acid consumption, coal consumption, and electricity consumption as parameters. The influence exerted by each parameter was analyzed by adding and subtracting 10 % to/from each. The results are shown in Table 4.

From Table 4, it can be seen that transportation distance had very low sensitivity, since the overall environmental impact change was insignificant, with the increase and decrease of this parameter. It also can be seen that electricity production in scenario 2, kraft paper production in scenario 3, and kraft paper production and polyethylene production in scenario 4 were the most sensitive factors in each scenario. Therefore, the way to significantly improve the environmental impact would be to increase the yield of recovery production related to each scenario.

6 Conclusions

An LCA for composite packaging waste management was carried out by estimating the environmental impacts of the four scenarios in China: landfill, incineration, paper recycling, and separation of polyethylene and aluminum. The scenarios were compared through the Eco-Indicator 99 method. The results of this LCA study have been discussed, and analysis has revealed that landfill is the worst waste management option, and that incineration is more environmentally friendly than paper recycling. A new scenario—separation of polyethylene and aluminum—was established, and inventory data were obtained from a demonstration project. The comparison result shows that separation of polyethylene and aluminum is the most environmental-friendly option; it can reduce the environmental impacts 12.8 % below those of the incineration scenario.

These research results will provide useful scientific information for policymakers in China to make decisions regarding the management of composite packaging waste. Incineration can reduce environmental impacts more in the respiratory inorganics category, and separation of polyethylene and aluminum can reduce them more in the fossil fuel category. If energy saving is the primary governmental goal, separation of polyethylene and aluminum would be the better choice, while incineration would be the better choice for emission reduction. These results will be also helpful for increasing the life cycle inventory database of China. However, this study investigated the topic only from an environmental point of view. It might be supported with other decision-making tools that consider the economic and social effects of waste management.

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